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Technical Fact Sheet – Nanomaterials

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TECHNICAL FACT SHEET – NANOMATERIALS

At a Glance

- Diverse class of small-scale substances that have structural components smaller than 100 nanometers (nm) in at least one dimension (Klaine and others 2008). Nanomaterials (NMs) include nanoparticles (NPs), which are particles with at least two dimensions between approximately 1 and 100 nm.
- Have high surface area to volume ratio and the number of surface atoms and their arrangement determines the size and properties of the NM.
- Can be categorized into three types: natural UFPs, incidental NMs and engineered NMs.
- Engineered NMs are used in a wide variety of applications, including environmental remediation, pollution sensors, photovoltaics, medical imaging and drug delivery.
- May be readily transported through media, usually over much greater distances than larger particles of the same composition.
- The mobility of NMs depends on factors such as surface chemistry and particle size, and on biological and abiotic processes in the media.
- May stay in suspension as individual particles, aggregate, dissolve or react with other materials.
- Characterization and detection technologies include differential mobility analyzers, mass spectrometry and scanning electron microscopy.

Introduction

This fact sheet, developed by the U.S. Environmental Protection Agency (EPA) Federal Facilities Restoration and Reuse Office (FFRRO), provides a summary of nanomaterials (NMs), including their physical and chemical properties; potential environmental and health impacts; existing federal and state guidelines; detection and treatment methods; and additional sources of information. This fact sheet is intended for use by site managers and other field personnel who may need to address or use NMs at cleanup sites or in drinking water supplies.

NMs are increasingly being used in a wide range of household, cosmetic and personal use, scientific, environmental, industrial and medicinal applications. NMs may possess unique chemical, biological and physical properties compared with larger particles of the same material (Exhibit 1). There is a growing concern about increased production and use of NMs and the lack of environmental health and safety data. Due to their widespread use, current research is focused on carbon-based, metal and metal oxides, quantum dots and nanosilver.

What are nanomaterials?

- NMs are a diverse class of small-scale substances that have structural components smaller than 100 nanometers (nm) in at least one dimension. NMs include nanoparticles (NPs), which are particles with at least two dimensions between approximately 1 and 100 nm (Klaine and others 2008). EPA refers to nano-sized particles that are natural or aerosol as ultrafine particles (UFPs).
- NMs and UFPs can be categorized into three types according to their source:
  - Natural UFPs include combustion products, viruses and sea spray.
  - Incidental NMs are generated by anthropogenic processes and include diesel exhaust, welding fumes and industrial effluents.
  - Engineered NMs are designed with very specific properties and are made through chemical and/or physical processes (Exhibit 1).
- NMs have high surface area to volume ratio and the number of surface atoms and their arrangement determines the size and properties of the NM (Sarma and others 2015).
- As of 2014, more than 1,800 consumer products containing NMs are on the market (Vance and others 2015).

Exhibit 1: Properties and Common Uses of NMs and UFPs

(EPA 2007, 2008a; Klaine and others 2008; Watlington 2005; Gil and Parak 2008; Luoma 2008; Cota-Sanchez and Merlo-Sosa 2015)

Types of NMs and UFPs (Occurrence)	Physical/Chemical Properties	Uses	Examples
Carbon-based (Natural or Engineered)	Stable, limited reactivity, excellent thermal and electrical conductivity.	Biomedical applications, battery and fuel cell electrodes, super-capacitors, adhesives and composites, sensors and components in electronics, aircraft, aerospace and automotive industries.	Fullerenes, multi-walled and single-walled carbon nanotubes (CNTs) and graphene oxide framework (GOF).
Metal Oxides (Natural or Engineered)	High reactivity, photolytic properties, and ultraviolet blocking ability. Capping agents are used in most cases.	Photocatalyst in solar cells, paints and coatings, cosmetics, ultraviolet blockers in sunscreen, cosmetics and bottle coatings and diesel fuel additive.	Titanium dioxide (TiO_2), zinc oxide (ZnO), cerium dioxide (CeO_2).
Zero-Valent Metals (Engineered)	High surface reactivity, varied properties based on reductant used and the reduction conditions.	Remediation of waters, sediments and soils to reduce contaminants such as nitrates, trichloroethylene, tetrachloroethylene and polychlorinated biphenyls.	Nanoscale zero-valent iron (nZVI), emulsified zero-valent nanoscale iron and bimetallic nanoscale particles.
Quantum Dots (Engineered)	Reactive core composed of metals or semiconductors controls the material's optical properties. Cores are surrounded by a shell that protects from oxidation.	Medical imaging, targeted therapeutics, solar cells, photonics and telecommunication.	Quantum dots made from cadmium selenide (CdSe), cadmium telluride (CdTe), indium phosphide (InP) and zinc selenide (ZnSe).
Dendrimers (Engineered)	Three-dimensional nanostructures engineered to carry molecules encapsulated in their interior void spaces or attached to the surface.	Drug delivery systems, polymer materials, chemical sensors and modified electrodes.	Hyperbranched polymers, dendrigraft polymers and dendrons.
Composite NMs (Engineered)	Composite NMs consist of multifunctional components and have novel electrical, catalytic, magnetic, mechanical, thermal or imaging features.	Potential applications in drug delivery and cancer detection. Also used in auto parts and packaging materials to enhance mechanical and flame-retardant properties.	Produced using two different NMs or NMs combined with larger, bulk-type materials. They can also be made with NMs combined with synthetic polymers or resins.
Nanosilver (Engineered)	High reactivity, composed of many atoms of silver, which can release silver ions, strong antimicrobial properties.	Medicine applications, water purification and antimicrobial uses, socks and other textiles, air filters, toothpaste, vacuum cleaners and washing machines.	Forms include colloidal silver, spun silver, nanosilver powder and polymeric silver composite.

How can nanomaterials affect the environment?

- Engineered NMs may be released into the environment primarily through industrial and environmental applications, improper handling or consumer waste (EPA 2007).
- NPs fate and transport in the environment are largely dependent on material properties such as surface chemistry, particle size and biological and abiotic processes in environmental media. Depending on these properties, NPs may stay in suspension as individual particles, aggregate, dissolve or react with other materials (EPA 2009; Luoma 2008).
- Some NMs are reported to be photoactive, but their susceptibility to photodegradation in the atmosphere has not been studied (EPA 2007).
- Although nZVI is widely used in site remediation, information is limited on its fate and transport in the environment. Research is ongoing to determine whether these NMs could migrate beyond the contaminated plume area and persist in drinking water aquifers or surface water (EPA 2008a).
- Many NMs containing inherently non-biodegradable inorganic chemicals such as ceramics, metals and metal oxides are not expected to biodegrade (EPA 2007).
- Oxidative stress and pathological changes in trout were observed after exposure to TiO_2 NPs (Federici and others 2007).
- Potential hepatic effects in rainbow trout after exposure to nanosilver and potential toxic effects to phytoplankton and zooplankton species were observed after exposure to some forms of nZVI (Keller and others 2012; Monfared and Soltani 2013).
- ZnO NPs affected the growth rate of the algae and suggested that the ZnO NPs were more toxic to the marine algae than bulk ZnO (Manzo and others 2013).
- Recent studies have shown the following:
  - Carbon fullerenes are insoluble and colloidal aggregates in aqueous solutions are stable for months to years, allowing for chronic exposure to biological and environmental systems (Hegde and others 2015).
  - Single-walled CNTs are not readily degraded by fungal cultures or microbial communities (Parks and others 2015).
  - Coatings on iron oxide NPs caused different toxic effects, which were linked to decreasing colloidal stability, the release of ions from the core material or the ability to form reactive oxygen species (ROS) in daphnids (Baumann and others 2014).
  - Nanosilver bacterial toxicity was associated with ROS and cell membrane damage (Priester and others 2014).
  - The degradation of a surface coating of nano-TiO_2 resulted in increased phototoxicity to a benthic organism (Wallis and others 2014).

What are the routes of exposure to nanomaterials?

- Human exposure to NMs may occur through ingestion, inhalation and dermal exposure. Occupational inhalation is a widely recognized route of human exposure (DHHS 2009).
- The small size, solubility and large surface area of NMs may enable them to translocate from their deposition site (typically in the lungs) and interact with biological systems. Circulation time increases drastically when the NMs are water-soluble (DHHS 2009; SCENIHR 2009).
- Some types of NMs that translocate into systematic circulation may reach the liver and spleen, the two major organs for detoxification and further circulatory distribution. Various cardiovascular and other extra pulmonary effects may also occur (Nel and others 2006; SCENIHR 2009).
- A recent study showed that nano-anatase TiO2 in higher dose caused serious damage to the liver, kidney, and myocardium of mice and disturbed the balance of blood sugar and lipid in mice (Liu and others 2009).
- Animal studies indicate that nano-TiO_2 may accumulate in the liver, spleen, kidney and brain after it enters the bloodstream through various exposure routes (Chang and others 2013).
- In humans, although most inhaled NMs remain in the lung, less than 1 percent of the inhaled dose may reach the circulatory system (SCENIHR 2009).
- Use of sunscreen products may lead to dermal exposure to NMs (TiO_2 and ZnO), depending on the properties of the sunscreen and the condition of the skin (EPA 2010; Mortensen and others 2008; Nel and others 2006).
- Ingestion exposure may occur from consuming NMs contained in drinking water or food (for example, fish) or from unintentional hand to mouth

transfer of NMs (DHHS 2009; Wiesner and others 2006).

What are the health effects of nanomaterials?

- The potential health effects of NMs are variable, depending on their characteristics. Clinical and experimental animal studies indicate that NMs can induce different levels of cell injury and oxidative stress, depending on their charge, particle size and exposure dose. In addition, particle coatings, size, charge, surface treatments and surface excitation by ultraviolet (UV) radiation can modify surface properties and thus the aggregation and potential biological effects of NMs (Chang and others 2013; Nel and others 2006).
- Some NMs, such as metal oxides, may generate ROS, which can lead to membrane damage, including increases in membrane permeability and fluidity. As a result, cells may become more susceptible to osmotic stress or impaired nutrient uptake (Klaine and others 2008).
- CNTs possess attributes similar to asbestos fibers and have been shown to cause inflammation and lesions as well as allergic immune responses in mice and rats. Several studies also report cellular DNA damage after exposure to single-walled CNTs (Hegde and others 2015).
- Several toxicological studies suggest fullerenes induce oxidative stress in living organisms (Hegde and others 2015).
- Biomarker responses were characterized following multi-walled CNT exposure to human liver cells (Henderson and others 2016).
- Toxicity of TiO_2 NPs have been studied extensively in recent years due to their use in sunscreen and cosmetics. Studies have shown exposure resulted in micoglia activation, ROS production, activation of signaling pathways that result in cell death, both in vitro and in vivo (Czajka and others 2015).
- The aging of nano-TiO2 in swimming pool water redistributed the coating and reduced its protective properties, thereby increasing reactivity and potential phototoxicity (Al-Abed and others 2016).
- Recent research has shown that TiO2 and ZnO can penetrate skin and be retained within the human stratum corneum and into some hair follicles (Hegde and others 2015).
- Metal-containing NMs, such as quantum dots and nanometals, may cause toxicity to cells by releasing harmful components such as heavy metals or ions (Klaine and others 2008; Luoma 2008; Powell and Kanarek 2006).
- Research has shown that NMs may stimulate or suppress immune responses (or both) by binding to proteins in the blood (Dobrovolskaia and McNeil 2007).
- Study results suggest that certain NMs may pose a respiratory hazard after inhalation exposure. For example, rodent studies indicate that single-walled CNTs may cause pulmonary inflammation and fibrosis. Exposures to TiO_2 NPs have also resulted in persistent pulmonary inflammation in rats and mice (EPA 2007; NIOSH 2011, 2013).
- Based on the results of available animal inhalation and epidemiologic studies, the National Institute for Occupational Safety and Health (NIOSH) has concluded that TiO_2 NPs may have a higher mass-based potency than larger particles and should be considered as a potential occupational carcinogen (NIOSH 2011).

Are there any federal and state guidelines or health standards for nanomaterials?

- Federal standards and guidelines:
  - The U.S. Food and Drug Administration (FDA) has finalized guidelines on the evaluation and use of NMs in FDA-regulated products. These guidelines focus on assessing safety, effectiveness and quality of products containing NMs, although the FDA does not make a categorical judgment on the safety or hazard of NMs (FDA 2014a, 2014b, 2014c and 2015a).
  - Many NMs are regarded as “chemical substances" under the Toxic Substances Control Act (TSCA) and therefore are subject to the requirements of the Act. EPA has already determined that CNTs are subject to reporting under Section 5 of TSCA. Under TSCA Section 8(a), EPA proposed a one-time reporting rule for NMs considered as existing chemicals (EPA 2008b and 2016; FDA 2015b).
  - If NMs enter drinking water or are injected into a well, they may be regulated under the Safe Drinking Water Act (EPA 2007). However, currently no maximum contaminant level goals (MCLGs) or maximum contaminant levels (MCLs) have been established for NMs.

Are there any federal and state guidelines or health standards for nanomaterials? (continued)

- NMs may be regulated under various programs such as Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), Clean Water Act (CWA) and Clean Air Act on a site-specific basis or if their use results in emissions of pollutants that are or could be hazardous (EPA 2007).
- State and local standards and guidelines:
  - In 2006, Berkeley, California, adopted the first local regulation specifically for NMs, requiring all facilities manufacturing or using manufactured NMs to disclose current toxicology information, as available (Berkeley 2006).
  - In 2010 and 2011, the California Department of Toxic Substances Control (CA DTSC) issued formal request letters to the manufacturers of certain CNTs, nanometal oxides, nanometals and quantum dots requesting information related to chemical and physical properties, including analytical test methods and other relevant information (CA DTSC 2013).

What detection and characterization methods are available for nanomaterials?

- The analysis of NMs in environmental samples often requires the use of multiple technologies in tandem. Characterization methods include spectroscopy, microscopy, chromatography centrifugation, filtration and others (Gmiza and others 2015).
- Single-particle mass spectrometry provides chemical analysis of NMs suspended in gases and liquids (SCENIHR 2009).
- Aerosol fractionation technologies (differential mobility analyzers and scanning mobility particle sizers) use the mobility properties of charged NMs in an electrical field to obtain size fractions for subsequent analysis. Multi-stage impactor samplers separate NM fractions based on the aerodynamic mobility properties of the NMs (EPA 2007).
- Expansion condensation particle counters measure aerosol particle number densities for size diameters as low as 3 nm. (Saghafifar and others 2009).
- Size-exclusion chromatography, ultrafiltration and field flow fractionation can be used for size fractionation and collection of NM fractions in liquid media (EPA 2007).
- NM fractions in liquid may be further analyzed using dynamic light scattering for size analysis and mass spectrometry for chemical characterization (EPA 2007).
- One of the main methods of analyzing single NM characteristics is electron microscopy. Scanning electron microscopy and transmission electron microscopy can be used to determine the size, shape and aggregation state of NMs below 10 nm (EPA 2007; SCENIHR 2006; Sanchis and others 2015).
- Atomic force microscopy can provide single particle size and morphological information at the nm level in air and liquid media (EPA 2007).
- Dynamic light scattering is used to characterize manufactured silver NMs and provides information on the hydrodynamic diameter of NMs in suspensions. It is capable of measuring NPs from a few nm in size, but is not suitable for environmental samples (EPA 2010).
- Other analytical techniques include X-ray diffraction to measure the crystalline phase and X-ray photoelectron spectroscopy to determine the surface oxidation states and chemical composition of NMs (EPA 2010).
- A recent laboratory study employed absorption-edge synchrotron X-ray computed microtomography to extract silver NM concentrations within individual pores in static and transport systems (Molnar and others 2014).

What technologies are being used to control nanomaterials?

- Coagulation is regarded as a critical process for the effective removal of NPs during water and wastewater treatment (Popowich and others 2015).
- Air filters and respirators are used to filter and remove NMs from air. A study found that membrane-coated fabric filters could provide an NM collection efficiency above 95 percent (Tsai and others 2012; Wiesner and others 2006).
- NMs in groundwater, surface water and drinking water may be removed using flocculation, sedimentation and sand or membrane filtration (Wiesner and others 2006), but a recent laboratory study using TiO2 NPs found that these typical treatment methods may be inadequate for particles smaller than 450 nm (Kinsinger and others 2015).
- A recent study stabilized silver NPs using different capping agents to control the transport of the NPs in porous media (Badawy and others 2013).

Where can I find more information about nanomaterials?

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